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RESEARCH MEMORANDUM

PRELIMINARY INVESTIGATION OF PERFORMANCE AND STARTING CHARACTERISTICS OF LIQUID FLUORINE - LIQUID OXYGEN MIXTURES WITH JET FUEL

By Edward A. Rothenberg and Paul M. Ordin

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Classification changed to Unclassified
By Authority of NASA Tech Pub Announcement #17
(OFFICER AUTHORIZED TO CHANGE)
14 Apr. 60
By.........
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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

PRELIMINARY INVESTIGATION OF PERFORMANCE AND STARTING CHARACTERISTICS OF LIQUID FLUORINE - LIQUID OXYGEN MIXTURES WITH JET FUEL

By Edward A. Rothenberg and Paul M. Ordin

SUMMARY

The performance of jet fuel with an oxidant mixture containing 70 percent liquid fluorine and 30 percent liquid oxygen by weight was investigated in a 500-pound-thrust, water-cooled engine operating at a chamber pressure of 300 pounds per square inch absolute. A one-oxidant-on-one-fuel skewed-hole impinging-jet injector was evaluated in a chamber of characteristic length equal to 50 inches.

A maximum experimental specific impulse of 268 pound-seconds per pound was obtained at 25 percent fuel (oxidant-fuel weight ratio, 2.9). This value corresponds to 96 percent of the maximum theoretical specific impulse based on frozen composition expansion. The maximum characteristic velocity obtained was 6050 feet per second at 23 percent fuel or 94 percent of the theoretical maximum.

The average thrust coefficient was 1.38 for the 500-pound-thrust combustion-chamber nozzle used, which was 99 percent of the theoretical (frozen) maximum. Three runs were made with the 70-30 fluorine-oxygen mixture with a triplet injector in a 100-pound-thrust engine.

Mixtures of fluorine and oxygen were found to be self-igniting with jet fuel with fluorine concentrations as low as 4 percent, when low starting propellant flow rates were used.

INTRODUCTION

The use of mixtures of liquid fluorine and liquid oxygen as rocket oxidants with jet fuel appears to show considerable promise for long-range missile applications. This combination seems to serve as an excellent compromise of performance, availability, and cost between the jet fuel - liquid oxygen and the liquid ammonia - liquid fluorine combinations.

Two fundamental approaches may be taken to the use of fluorine with the jet fuel - oxygen propellant combination. The first is to obtain the highest performance possible with the three-component system. North American Aviation and Aerojet-General have considered the use of fluorine-oxygen mixtures in this respect. Theoretical calculations made by the Jet Propulsion Laboratory (ref. 1) indicate that the

gasoline-fluorine propellant combination offers no performance advantage over gasoline-oxygen. The relatively low performance with fluorine is almost to be expected when the molecular weights and thermodynamic properties of the carbon fluorides are considered. Higher performance is obtainable with mixtures of oxygen and fluorine because of the substitution of carbon oxides for the fluorides. It would appear, then, that maximum performance would occur with a mixture whose products of combustion, assuming that oxidation of the fuel occurred selectively, were for the most part carbon oxides and hydrogen fluoride. This particular mixture would contain approximately 70 percent fluorine and 30 percent oxygen by weight.

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The second approach to the use of the fluorine - oxygen - jet fuel propellant combination focuses attention on mixtures having low concentrations of fluorine, 10 percent or less. The addition of small quantities of fluorine to oxygen should result in somewhat higher performance and tend to make the combination self-igniting. The possibility also exists that if the concentration of fluorine is low, the handling of the mixture would be about the same as the handling of liquid oxygen.

The purposes of the present work were: (1) with a minimum of injector study, to evaluate experimentally the performance of a mixture containing 70 percent fluorine and 30 percent oxygen with jet fuel; and (2) to explore the possibility of obtaining spontaneous ignition with mixtures of oxygen and fluorine containing less than 10 percent fluorine with jet fuel.

The performance tests were made in a 500-pound-thrust engine at a chamber pressure of 300 pounds per square inch absolute. A one-oxidant-on-one-fuel skewed-hole impinging-jet injector was used in a water-cooled engine with a characteristic length L^* (ratio of chamber volume to throat cross-sectional area) of 50 inches. Specific impulse, characteristic velocity, and thrust coefficient were measured and are presented as curves of the performance parameters plotted against weight percent fuel. Data for three runs made in a 100-pound-thrust unit with the 70 percent fluorine - 30 percent oxygen mixture are included on the curves.

The starting tests with mixtures containing from 4 to 11 percent fluorine were run in a chamber designed to deliver 100 pounds thrust at a chamber pressure of 300 pounds per square inch absolute. A conventional one-oxidant-on-one-fuel impinging-jet injector was used. The data obtained from these tests are, for the most part, of a qualitative nature and are presented in tabular form accompanied by descriptions of observations made throughout the program.

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EQUIPMENT AND PROCEDURE

Test Installation

The performance and ignition tests were carried out on two separate thrust stands operating from common propellant supply systems. Both thrust stands were bearing-type, pivoted stands. The 500-pound-thrust engine was mounted horizontally, while the 100-pound-thrust unit fired at a downward angle of 30°.

A flow diagram of the propellant systems used is shown in figure 1. The facilities described were similar to those used in reference 2.

The oxidant flow system was made entirely of brass, nickel, and monel tubing and fittings. The monel oxidant supply tank was suspended from a cantilever weigh-beam and immersed in a liquid nitrogen bath.

Stainless steel was used throughout the fuel flow system. The fuel supply tank, which was also suspended from a cantilever weigh-beam, was immersed in a water bath to provide a buoyant force to nearly counterbalance the weight of the empty tank.

Pressurized dry helium gas was used to force the propellants from the tanks to the rocket engines.

Engine Assemblies

The 500- and 100-pound-thrust 50 L^* engines were both designed to operate at a chamber pressure of 300 pounds per square inch absolute and chamber-to-throat area ratios of 10.5 and 16.5, respectively. The combustion chambers and nozzles had annular coolant passages. Sketches of the 500- and 100-pound-thrust chambers and nozzles are shown in figures 2(a) and (b), respectively.

The performance and operational characteristics of a doublet one-oxidant-on-one-fuel skewed-hole injector, which had 20 pairs of orifices, was studied in the 500-pound-thrust engine. A photograph and a cross-sectional sketch of the injector are presented in figure 3(a). A photograph and a cross-sectional sketch of the triplet impinging-jet injector used with the 100-pound-thrust engine are shown in figure 3(b). The injector had four sets of holes; each set had two oxidant jets and one fuel jet impinging at a common point.

A simple doublet-type injector (fig. 4) with eight pairs of holes was used for the starting tests in the 100-pound-thrust engine.

Propellants

The initial performance tests were made with JP-3 fuel. The final three performance runs and all the starting tests were made with JP-4 fuel. The analysis of the jet fuels is presented in table I.

Liquid oxygen for the fluorine-oxygen mixtures was condensed from commercial cylinders of gaseous oxygen. Gaseous fluorine of at least 98 percent purity was obtained in cylinders, each containing 6 pounds under a pressure of approximately 350 pounds per square inch gage. 3130

The oxidant mixture was prepared before each run by condensing the required amount of oxygen into the oxidant supply tank, then condensing the quantity of fluorine needed into the same tank. The quantities of oxygen and fluorine added were determined by the change in tank weight as indicated by a strain gage cemented to the cantilever weigh-beam. After both the oxygen and fluorine had been added, helium gas was bubbled through the liquid to insure sufficient mixing.

To determine whether a homogeneous mixture can be obtained and to observe the mixing characteristics of the fluorine and oxygen, a small quantity of the mixture was prepared in glass apparatus at the outset of the investigation. Oxygen was condensed first in the collection vessel. When the fluorine was added the entire solution changed color almost immediately from the light blue of oxygen to yellow as the fluorine condensed. When all the fluorine had been added, the solution was a uniform yellow-orange except for a slightly darker portion around the exit of the delivery tube. A small amount of helium bled through the tube quickly dispersed this assumed concentration of fluorine. It will be shown later that there were no large changes in thrust or chamber pressure during consumption of all the oxidant, which also indicates that the oxidant was homogeneous.

Instrumentation

Thrust and propellant flows were measured with calibrated strain gages cemented to cantilever weigh-beams. The output of the strain gages was recorded on self-balancing potentiometers. The precision of the measurement, including variation of calibration constants and interpretation of chart readings, was approximately 2 percent for the propellant flows and for the thrust.

Propellant injection pressures and combustion-chamber pressure were measured both by Bourdon tube type pressure recorders and by variable-reluctance-type pressure pick-ups whose output was recorded on an 18-channel oscillograph. Self-balancing potentiometers recorded the output of iron-constantan thermocouples to measure propellant injection temperatures.

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Procedure

The jet fuel was loaded into the fuel supply tank directly from the storage drum after all propellant valves and fittings in the test installation were pressure-checked and purged with dry helium.

After the oxidant mixture was condensed into the supply tank, both propellant tanks were pressurized. A precooling flow of liquid nitrogen was passed through the oxidant flow line until the oxidant fire valve was opened.

RESULTS AND DISCUSSION

Performance Evaluation of 70 Percent Fluorine - 30 Percent Oxygen Mixture with Jet Fuel

The experimental performance obtained with the 70 percent fluorine - 30 percent oxygen mixture with jet fuel is compared with theoretical values calculated on the basis of frozen composition expansion.

The experimental performance data are presented in table II. Representative chamber pressure and thrust records (fig. 5) indicated that the starts were smooth with rapid build-up of thrust and chamber pressure. The runs were steady from start to shutdown (when oxidant tank was emptied).

Experimental specific impulse. - The curve of experimental specific impulse against weight percent fuel (and oxidant-fuel ratio O/F) is shown in figure 6, along with the theoretical curve. The data are uncorrected for chamber pressure variation from the base of 300 pounds per square inch absolute and for the heat rejection to the engine walls. The experimental curve is drawn through the data obtained with the 500-pound-thrust unit and the doublet skewed-hole injector. The maximum experimental specific impulse was 268 pound-seconds per pound at 25 percent fuel (O/F, 2.9), which is approximately 96 percent of the theoretical (frozen) maximum of 278 pound-seconds per pound at 21 percent fuel (O/F, 3.9). The experimental curve is drawn dotted beyond 27 percent fuel because of the discrepancy between the performance obtained for the runs at 29 and 33 percent fuel. Both these runs were smooth and of sufficient duration to achieve steady-state operation. The chamber pressure for the run at 29 percent fuel was 235 pounds per square inch absolute, while for the run at 33 percent fuel, the chamber pressure was 275 pounds per square inch absolute. The difference in chamber pressure between the two runs hardly accounts for the performance difference on a theoretical basis and indicates either a large change in injector characteristics or an unknown error.

The theoretical specific impulse peaks at approximately 21 percent fuel while the experimental curve reaches a maximum at 25 percent fuel.

The difference in the position of the theoretical and experimental peak performance may be due, in part, to the injector design because the mixing characteristics of the doublet-type injector are sensitive to relative changes between fuel and oxidant flow.

The performance obtained for the three runs with the 100-pound-thrust engine and the triplet injector are also plotted in figure 6. The runs were made at 17 to 21 percent fuel and gave specific impulse values of 235 to 245 pound-seconds per pound, which are comparable to those obtained with the 500-pound-thrust unit at the same fuel percentages. 3130

Characteristic velocity and thrust coefficient. - The experimental curve of characteristic velocity against weight percent fuel (and O/F weight ratio) is presented in figure 7 along with the theoretical (frozen) curve. The maximum experimental value of 6050 feet per second was obtained at 23 percent fuel; this value was 94 percent of the theoretical maximum of 6460 feet per second which occurred at 21 percent fuel. The curve exhibits trends similar to those of the specific impulse curve with regard to the position of peak performance and the discrepancy between the runs made at 29 and 33 percent fuel. The three runs made in the 100-pound-thrust engine indicated a maximum characteristic velocity of 6100 feet per second at 21 percent fuel, which would be compared with 5880 feet per second for the 500-pound-thrust engine at the same fuel percentage.

The thrust coefficient values for the 500-pound-thrust unit are plotted in figure 8. The average value over the entire range of fuel percentages was 1.38, which is 99 percent of the theoretical value of 1.39. The thrust coefficient values obtained with the 100-pound-thrust engine are also shown on the curve and have an average value of 1.28.

The 100-pound-thrust unit produced higher characteristic velocities but lower thrust coefficients than the 500-pound-thrust engine, which resulted in comparable specific impulse values for the two. These results indicate that the triplet was the better injector.

Starting. - The 70 percent fluorine - 30 percent oxygen mixture was self-igniting with jet fuel. The starting propellant flow rates were generally of the order of 150 percent of the design flows for the engine. (The design flows are those which are required to produce 500 pounds thrust at a chamber pressure of 300 pounds per square inch absolute.) The high starting flows are the result of a preset, constant injection pressure (550 to 600 lb/sq in. abs) which gives a maximum pressure drop across the injection orifices prior to combustion chamber pressure build-up. Both fuel and oxidant leads were used with no apparent effect on the start.

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Operational notes. - Although the doublet skewed-hole injector performed well, it was subject to burnout. The portion of the injector face which was oxidant-cooled burned out and was repaired on several occasions. Most of the burnouts occurred within the first 5 seconds of operation, although on two occasions they occurred after 15 seconds of normal operation. The burnouts occurred in the area of the injector face that was 90° from the oxidant feed tubes (see fig. 3(a)), where the oxidant velocity would be zero if a symmetrical flow distribution were assumed. The susceptibility of the injector to burnout may have been increased after the first burnout because the welds, which were necessary to repair the injector face, were not finish-machined and resulted in a heavier, rough-surfaced area on the injector face.

Large amounts of a black precipitate appeared in the water which was used to quench the rocket exhaust during the runs. An examination of the inner walls of the rocket engine after each run revealed a thin, nonuniform coating of the carbonaceous material. An analysis of a sample taken from the engine after a run showed the material to be almost pure carbon. It was not possible to determine whether the carbon was deposited during the run or was merely a result of starting or shutdown operations.

Starting Experiments with Jet Fuel and Fluorine-Oxygen Mixtures Containing from 4 to 11 Percent Fluorine

The self-igniting starting tendencies of jet fuel with mixtures of fluorine and oxygen containing from 4 to 11 percent fluorine were examined in rocket engines designed to deliver 100 pounds thrust. The results, together with the propellant lead and lead time used, for each of the starts attempted, are listed in table III.

Starting with initial flows from 150 to 200 percent of design flows. - Five successful starts were achieved with a mixture containing 11 percent fluorine by the same starting procedure which proved satisfactory for the 70 percent fluorine mixture; starting flows were 150 to 200 percent of the design flows for the engine. Two of the starts, one with an oxidant lead and one with a fuel lead, indicated surges of chamber pressure after ignition and were termed rough starts.

Three attempts to start a 5 percent fluorine mixture, again with initial flows of approximately 150 percent of the design flows, resulted in one successful start which was made with a fuel lead. Explosions resulted in both the other attempts, one of which was made with an oxidant lead.

One starting attempt made with a 4 percent fluorine mixture at starting flows of approximately the design value resulted in an explosion.

Flow records were not obtained for the run; however, it was noticed that, when the explosion took place, the injection pressures indicated propellant flow rates approximately equal to the design flows for the engine.

Starting with initial flows less than 50 percent of design flows. - Oxidant mixtures containing 6 and 4 percent fluorine were started successfully with jet fuel when the starting flows were reduced to less than 50 percent of the design flows. The lower flows were obtained by reducing the propellant injector pressure drop. After ignition occurred, the tank pressures were increased until design flows were reached. 3130

Helium was bled into the fuel flow line to atomize the fuel, which aided in fuel distribution and mixture preparation in the combustion chamber. The helium flow was stopped, after ignition, as the fuel flow rate was increased. Fuel leads were used for all the reduced starting flow tests.

Two successful starts were made with a 6 percent fluorine mixture and four with a 4 percent fluorine mixture. The helium bleed was found to be unnecessary for a successful start and was not used for all the tests.

In all the starts made with reduced flows, there was a delay of 10 to 30 seconds from the time the oxidant fire valve was opened until a pressure was noticed in the chamber, which was the indication that ignition had occurred. The propellant flow and injection pressure records indicated that throughout most of the preignition period the oxidant flow rate was so low as to be unreadable.

Discussion. - Since the results indicate good starting at high flows at 11 percent fluorine but not at 5 percent fluorine, it is apparent that there is an increase in ignition delay with a decrease in fluorine concentration. A long ignition delay would allow propellant to accumulate in the combustion chamber, which could result in an explosion. Propellant accumulation was apparently avoided through the use of starting flows which were less than 50 percent of the design flows and successful starts were made with the 4 percent fluorine mixture.

In the case of the reduced flow starts, with propellant injection pressures as low as 50 pounds per square inch, inadequate precooling of the oxidant flow line would account for the 10 to 30 second delay from the time the oxidant fire valve was opened until ignition occurred. Vaporization of the oxidant as it flowed through the line would greatly reduce the oxidant flow rate. The low oxidant flow rate would result in an extremely fuel-rich mixture, which was not self-igniting, in the chamber. Ignition did occur when the oxidant flow line had cooled sufficiently to permit an oxidant flow high enough to produce a combustible mixture.

The results of the tests made with 4 percent fluorine mixtures suggest the presence of a limited range of fuel-oxidant mixtures which are self-igniting. Although the effect of fuel-oxidant ratio was not studied in this preliminary investigation, it would seem that reliable starts could be obtained with gaseous oxidant provided the fuel flow is decreased correspondingly.

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CONCLUDING REMARKS

A comparison can be made between the experimental performance of the ammonia-fluorine and the jet fuel - 70 percent fluorine - 30 percent oxygen mixture propellant combinations. An experimental investigation indicated a maximum specific impulse of 270 pound-seconds per pound for ammonia-fluorine in a 100-pound-thrust engine with a triplet injector at a chamber pressure of 300 pounds per square inch absolute (ref. 3). An experimental maximum of 268 pound-seconds per pound is indicated for the jet fuel - fluorine - oxygen combination in a 500-pound-thrust engine with a doublet skewed-hole injector at the same chamber pressure. Although two different engine sizes and injectors were used and the comparison is not exact, experimental results thus far show little performance advantage of ammonia-fluorine over jet fuel with the fluorine-oxygen mixture.

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SUMMARY OF RESULTS

The performance of a mixture of 70 percent fluorine - 30 percent oxygen with jet fuel was evaluated in a 500-pound-thrust engine with a characteristic length L^* of 50 inches at a chamber pressure of 300 pounds per square inch absolute. A one-oxidant-on-one-fuel skewed-hole impinging-jet injector was used throughout the investigation. The results may be summarized as follows:

1. The curve of experimental specific impulse against weight percent fuel indicated a maximum of 268 pound-seconds per pound at 25 percent fuel (oxidant-fuel ratio O/F, 2.9), approximately 96 percent of the theoretical maximum based on frozen composition expansion.

2. The maximum characteristic velocity was 6050 feet per second at 23 percent fuel (O/F, 3.35), 94 percent of the theoretical frozen maximum.

3. The arithmetic average of experimental thrust coefficients was 1.38, 99 percent of the theoretical maximum value.

4. Three runs made with a 100-pound-thrust, 50 L^* engine and a triplet injector with four sets of holes gave specific impulse values comparable to those obtained with the 500-pound-thrust engine at the same

percent fuel. Characteristic velocity values were higher and thrust coefficient values lower than those obtained with the 500-pound-thrust engine.

5. The 70 percent fluorine - 30 percent oxygen mixture with jet fuel was self-igniting; starts were successful with both fuel and oxidant leads.

6. Direct addition of fluorine to liquid oxygen (liquid nitrogen cooled) was successful in producing what appeared to be a homogeneous 3130
oxidant mixture.

The self-igniting starting tendencies of fluorine-oxygen mixtures containing less than 11 percent fluorine with jet fuel were observed in 100-pound-thrust engines operating at a chamber pressure of 300 pounds per square inch absolute. A doublet one-oxidant-on-one-fuel impinging-jet injector was used. The results may be summarized as follows:

1. Successful starts were achieved with a 11 percent fluorine - 89 percent oxygen mixture at starting flow rates of approximately 150 percent of the design flows, four with oxidant leads and one with a fuel lead.

2. Four starting attempts with a 5 percent fluorine - 95 percent oxygen mixture at starting propellant flow rates of approximately 150 percent of the design flows resulted in one successful start with a fuel lead, two explosions with a fuel lead, and one explosion with an oxidant lead.

3. Six successful starts were achieved with mixtures containing from 4 to 6 percent fluorine with fuel leads and reduced starting flows.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, October 26, 1953

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2. Ordin, Paul M., Rothenberg, Edward A., and Rowe, William H.: Investigation of Liquid Fluorine and Hydrazine-Ammonia Mixture in 100-Pound-Thrust Rocket Engine. NACA RM E52H22, 1952.

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TABLE I. - PROPERTIES OF JET FUELS

Properties	JP-3	JP-4
A.S.T.M. distillation D86-52, °F		
Percentage evaporated		
Initial point	117	156
5	155	189
10	187	210
20	234	221
30	266	235
40	291	246
50	312	259
60	333	268
70	358	283
80	394	300
90	449	325
95	487	355
End point	523	442
Residue, percent	1.3	1.2
Loss, percent	1.3	0.3
Reid vapor pressure, lb/sq in.	5.4	2.4
Hydrogen-carbon ratio	0.170	0.174
Heat of combustion, Btu/lb	18,700	18,725
Specific gravity, 60/60 °F	0.765	0.751
Gravity, °API	53.4	57.0
Aniline point, °F	134.6	131.4

TABLE II. - SUMMARY OF EXPERIMENTAL PERFORMANCE OF JET FUEL WITH 70 WEIGHT PERCENT FLUORINE - 30 WEIGHT PERCENT OXYGEN MIXTURE

Run time, sec	Fuel	Fluorine in oxidant, weight percent	Fuel, weight percent	Total propellant flow, lb/sec	Thrust, lb	Specific impulse, lb-sec/lb	Combustion-chamber pressure, lb/sq in. abs	Characteristic velocity, ft/sec	Thrust coefficient
500-Pound-thrust, 50 L* engine; doublet skewed-hole impinging-jet injector									
17	JP-3	69	19.2	2.02	491	243	297	5690	1.38
17	JP-3	70	19.6	1.96	489	250	290	5720	1.41
18	JP-3	70	21.2	1.92	504	262	300	6030	1.38
20	JP-3	70	28.8	1.74	370	212	235	5210	1.31
4	JP-4	71	25.3	1.98	528	266	305	5940	1.44
15	JP-4	68	27.2	1.91	516	269	292	5910	1.44
6	JP-4	70	32.9	1.83	439	240	275	5800	1.33
100-Pound-thrust, 50 L* engine; two-oxidant-one-fuel impinging-jet injector									
12	JP-3	70	16.7	0.396	97	245	309	6100	1.29
6	JP-3	70	20.9	.388	94	245	304	6140	1.28
11	JP-3	70	19.9	.373	87	234	285	5980	1.26

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TABLE III. - SUMMARY OF STARTING TESTS OF JET FUEL WITH MIXTURES OF FLUORINE AND OXYGEN IN A 100-POUND-THRUST ROCKET ENGINE

Fluorine in oxidant, weight percent	Lead to chamber	Lead time, sec	Remarks
Starting flows, 150 to 200 percent of design flows			
11	Oxidant	0.6	Smooth start
11	Oxidant	.6	Smooth start
11	Oxidant	.7	Smooth start
11	Oxidant	.6	Rough start
11	Fuel	1.0	Rough start
5	Fuel	1.6	Rough start
5	Fuel	1.2	Explosion
5	Oxidant	.6	Explosion
4	Fuel	1.4	Explosion[a]
Starting flows, less than 50 percent of design flows			
6	Fuel	---	Smooth start, helium bleed for fuel atomization
6	Fuel	1.7	Smooth start
4	Fuel	1.5	Smooth start, helium bleed for fuel atomization
4	Fuel	1.6	Smooth start, helium bleed for fuel atomization
4	Fuel	1.8	Smooth start
4	Fuel	1.5	Smooth start

[a]Starting flows approximately 100 percent of the design flows.

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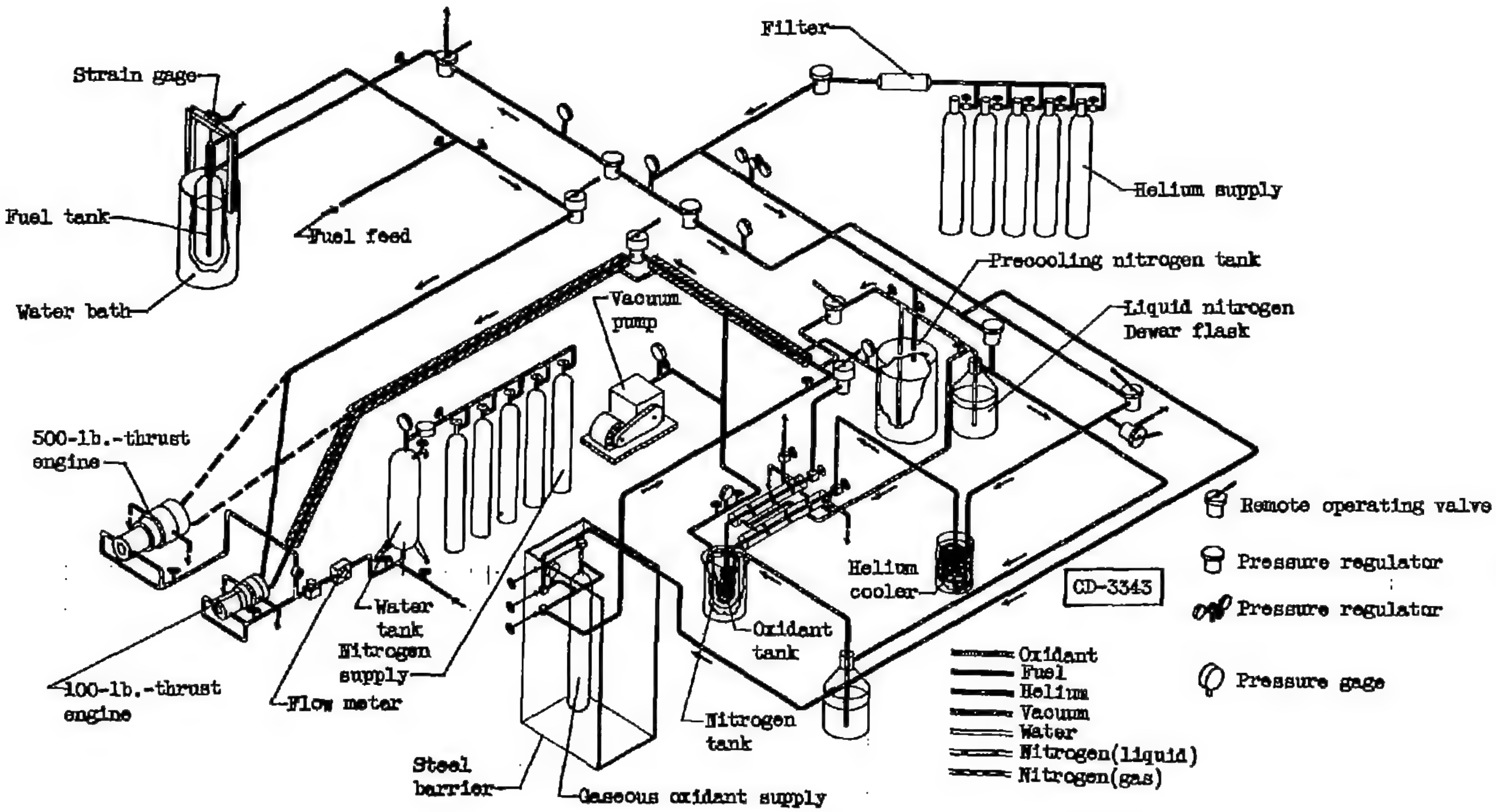

Figure 1. - Diagrammatic sketch of apparatus for performance and starting tests of fluorine-oxygen mixtures with jet fuel.

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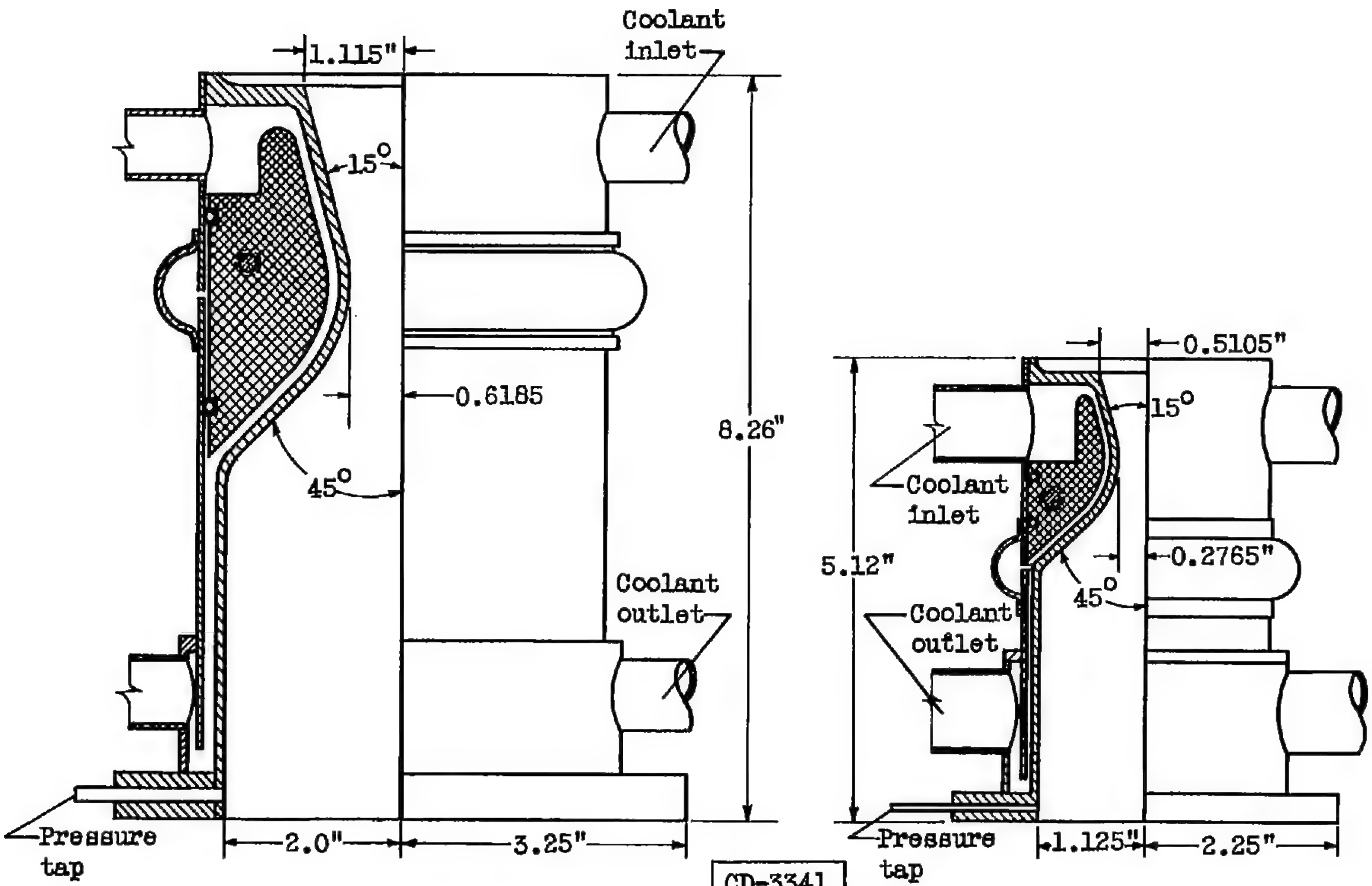

(a) 500-Pound-thrust-engine.

(b) 100-Pound thrust engine

Figure 2. - Diagrammatic sketches of combustion chamber and nozzle assemblies for engines of 50-inch characteristic length.

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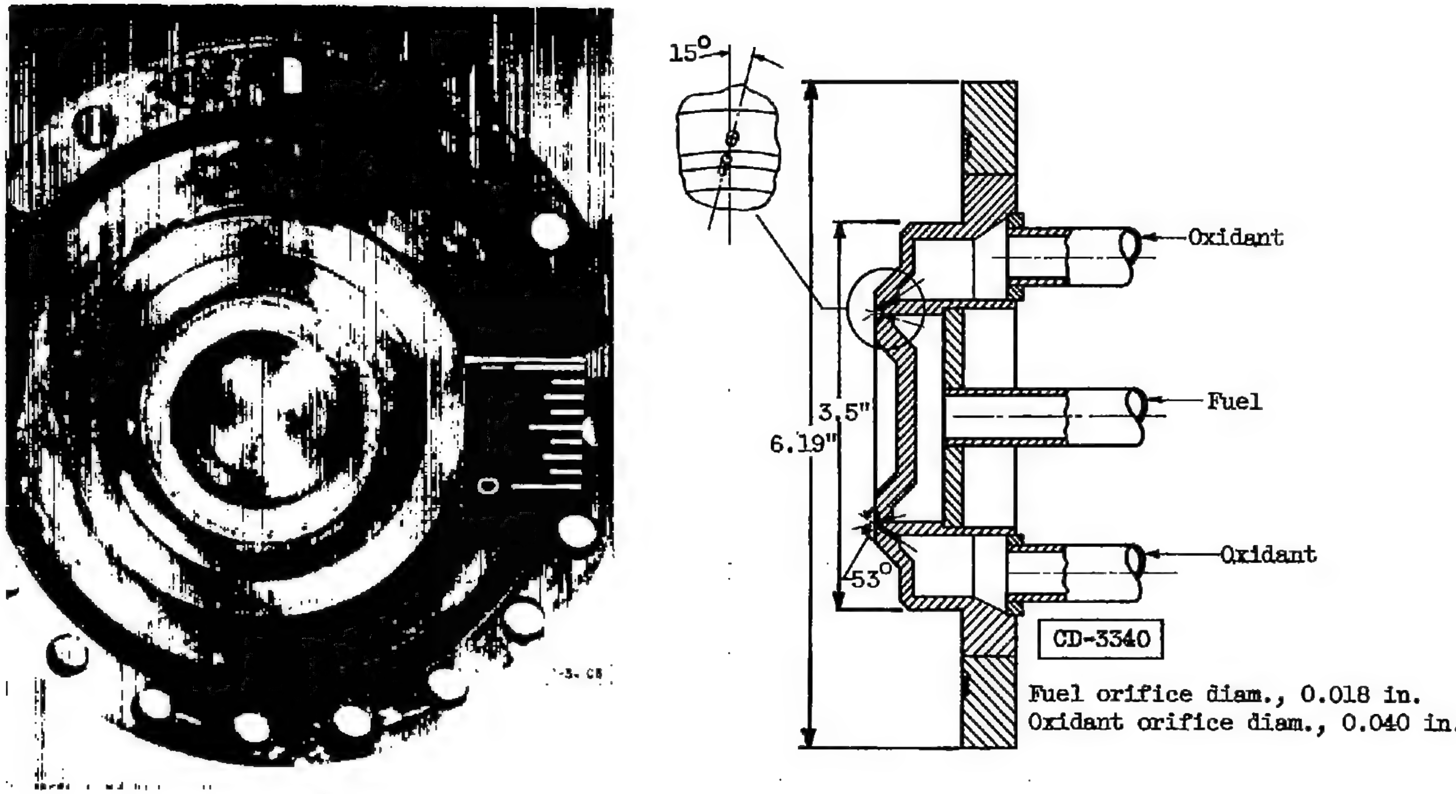
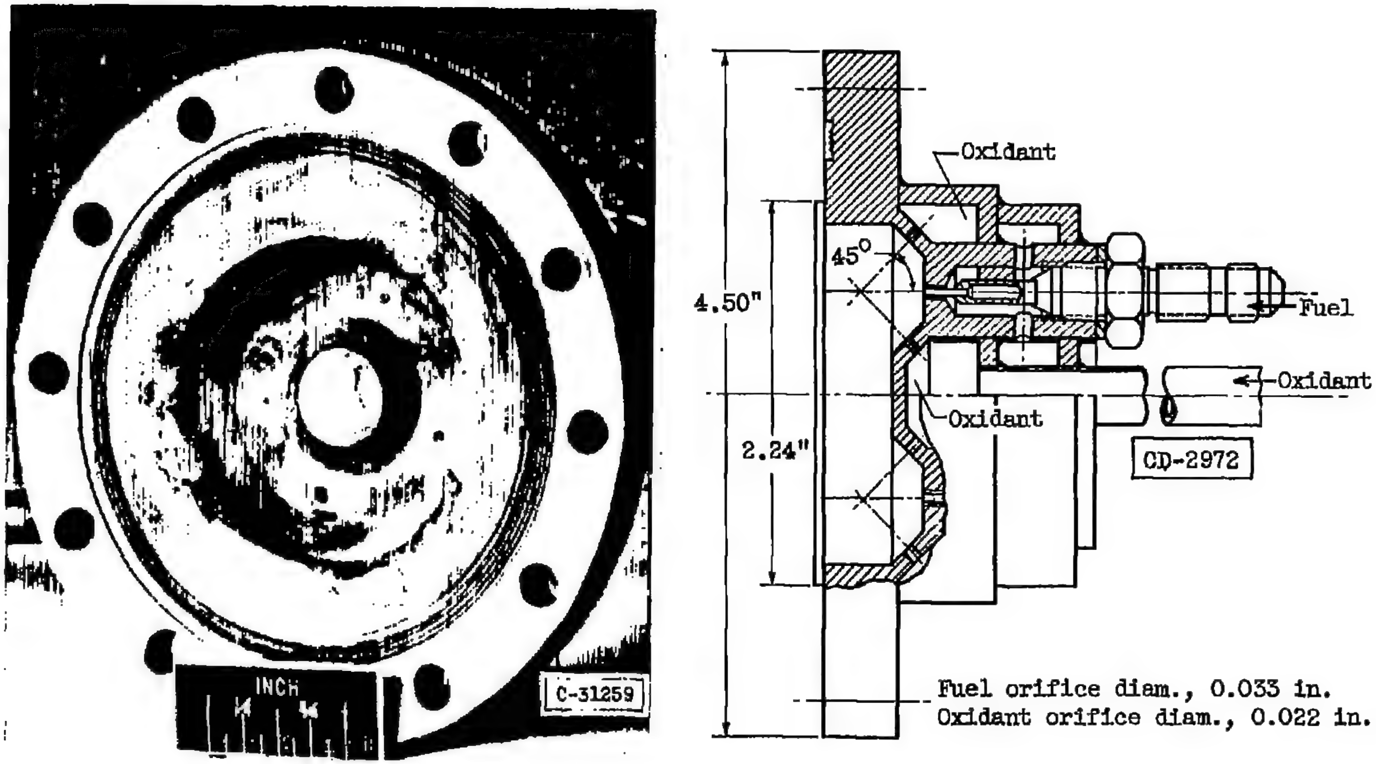


(a) Skewed-hole impinging-jet injector; 20 sets of one-oxidant-on-one-fuel jets; 500-pound-thrust engine.

Figure 3. - Injectors used for performance investigation.



(b) Impinging-jet injector; four sets of two-oxidant-on-one-fuel jets; 100-pound-thrust engine.

Figure 3. - Concluded. Injectors used for performance investigation.

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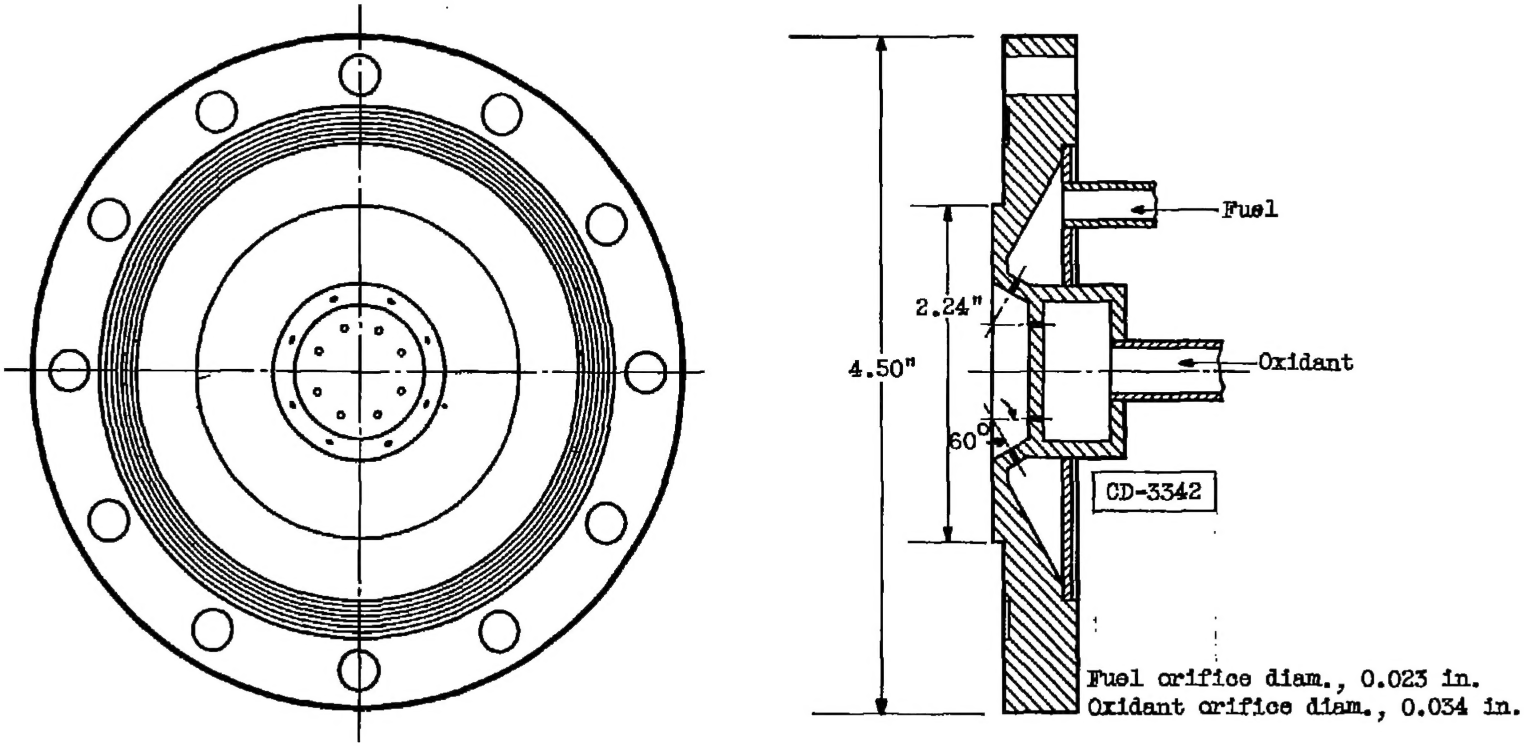
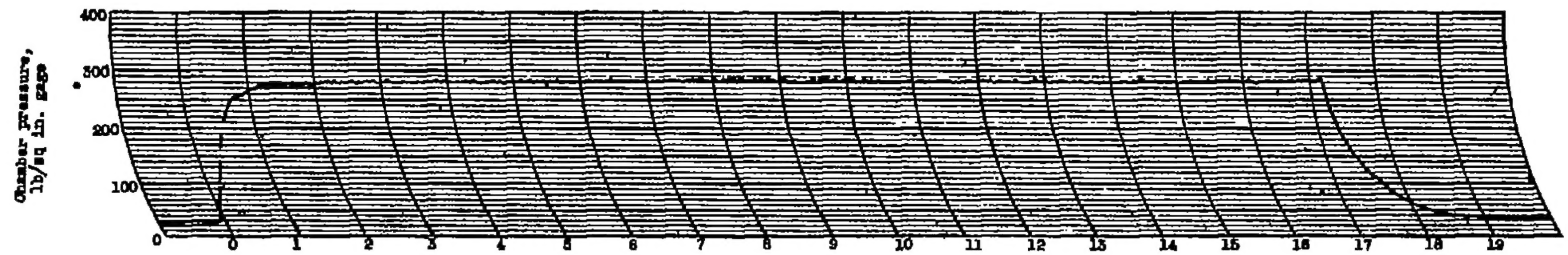
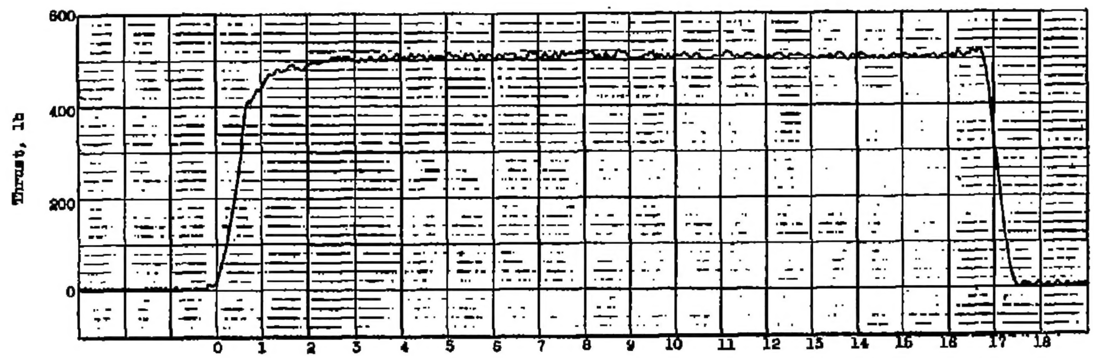


Figure 4. - Impinging-jet injector used for starting tests. Eight sets of one-oxidant-on-one-fuel jets; 100-pound-thrust engine.



(a) Chamber pressure.



(b) Thrust.

Figure 5. - Chamber pressure and thrust records for rocket engine experiment with jet fuel and oxidant mixture of 70 percent fluorine - 30 percent oxygen.

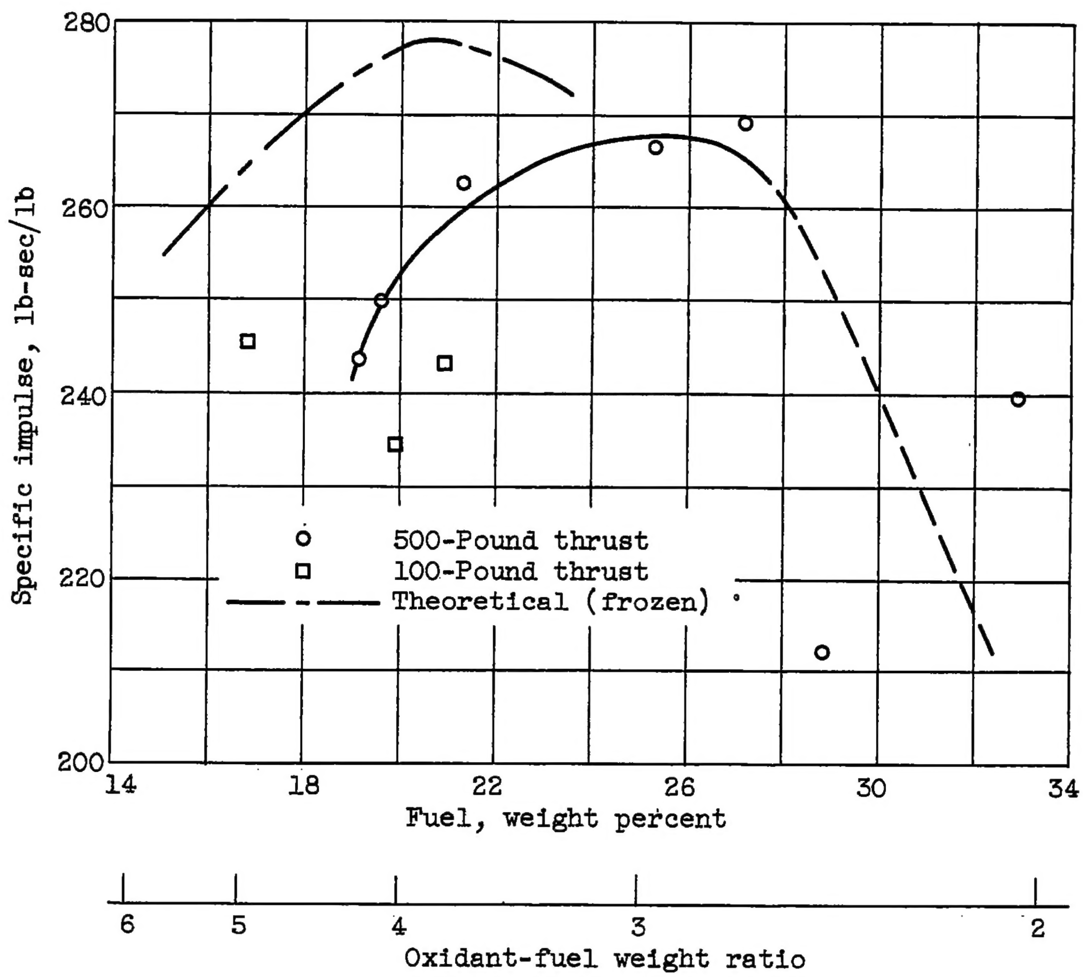


Figure 6. - Theoretical and experimental specific impulse of mixture of 70 percent fluorine - 30 percent oxygen with jet fuel. Chamber pressure, 300 pounds per square inch absolute.

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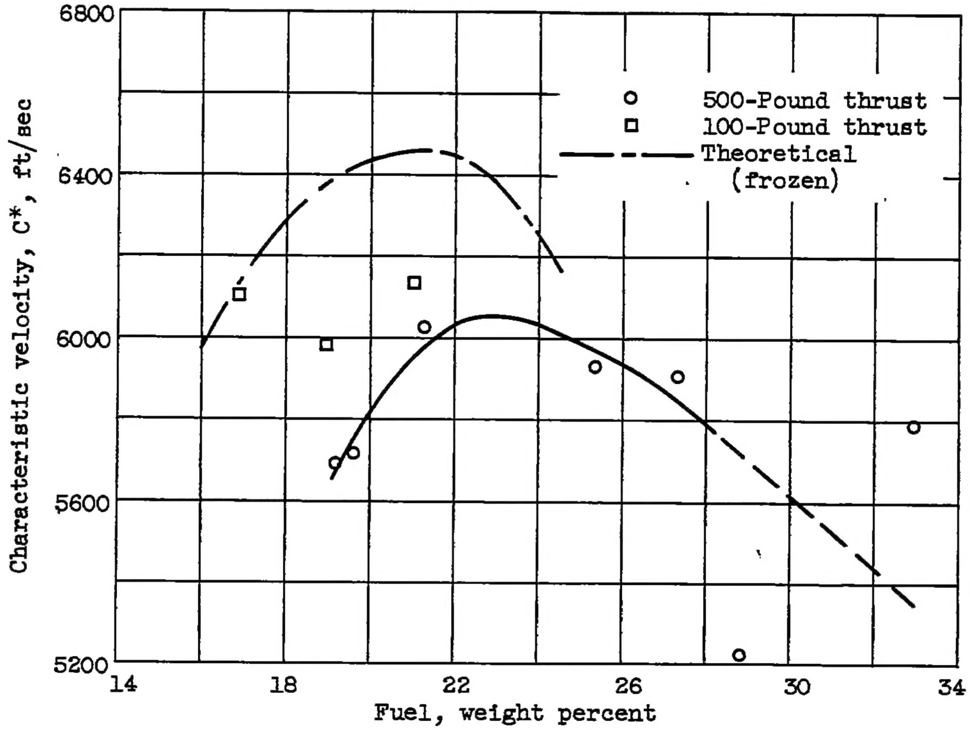

Figure 7. - Theoretical and experimental characteristic velocity for mixture of 70 percent fluorine - 30 percent oxygen with jet fuel. Chamber pressure, 300 pounds per square inch absolute.

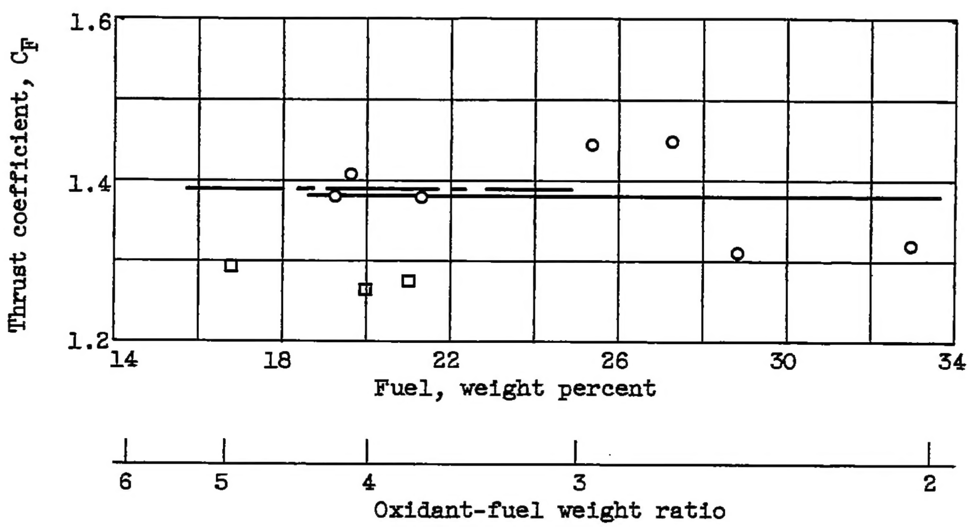

Figure 8. - Theoretical and experimental thrust coefficient for mixture of 70 percent fluorine - 30 percent oxygen with jet fuel. Chamber pressure, 300 pounds per square inch absolute.

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